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Simulation of potential impacts of man-made land use changes on U.S. summer climate under various synoptic regimes

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Abstract. This study evaluates impacts of land use changes due to human settlement on regional summer climate over the central and western United States by performing 30-day simulations during normal, drought, and flood years. Under current land use the simulated evapotranspiration increased noticeably over the central United States where grassland has been replaced by crops. Simulated evapotranspiration decreased slightly in the western United States. These changes produced wetter and cooler surface air over the central United States and slightly drier and warmer air over the western United States. Responses of surface fluxes and thus screen height variables to land use changes were consistent from year to year, whereas rainfall showed strong interannual variations because of the combination of various dynamic processes involved in precipitation. For normal year conditions, average evapotranspiration and rainfall under current land use increased by 18% and 8%, respectively, over the central United States, whereas they slightly decreased in the western United States. In both flood and drought years, current land use exhibited a rainfall increase in the western United States and a decrease over the central United States. The decrease of rainfall with increased evapotranspiration in the central United States was likely associated with weakening of the dynamic forcing needed to produce precipitation.

1. Introduction

Land use modifications by human activities, such as deforestation, urbanization, and agricultural practice, have long been believed to influence climate [e.g., *Charney et al.*, 1977; *Dickinson and Henderson-Sellers,* 1988; *Watson et al.*, 1995]. Early European settlement of the United States reduced some native forests and grassland during the nineteenth century, and then massive immigration and associated agricultural practices extensively changed use of the land. In the late 1700s, before major European immigration, the landscape of North America was mostly composed of forests, grass prairie, and swamps, whereas the present landscape is mainly composed of forests and agricultural land and grassland. This is especially true over the midwest and the Great Plains, the heavily cultivated areas.

It is of interest from a climate point of view to examine impacts of modification in land use on basic meteorological variables. Such an evaluation is difficult because no detailed observations document the temporal trends of basic meteorological variables since the European settlement in North America, although somewhat detailed observations of such variables are available over a shorter period, mostly the last 100 years [*Plantico et al.*, 1990]. One means to infer the effects of land use changes on climate is by use of a numerical model. Few studies have used regional climate models to evaluate climate impacts of land use over the United States, and most of these studies evaluated effects of only one aspect of land use (e.g., *Giorgi et al.* [1996] for soil moisture and *Segal et al.* [1998] for irrigation). To the authors' knowledge only two modeling studies have evaluated the effects on climate over the United States due to historical changes in land use: *Copeland et al.* [1996], who reported a July simulation for a normal year using a regional model; and *Bonan* [1997], who carried out a 5-year global simulation. Some differences in main simulated patterns emerge, although the two studies cannot be compared directly in detail. Experience with global (Atmospheric Model Intercomparison Project (AMIP), [*Gates,* 1992]) and regional (Project to Intercompare Regional Climate Simulations (PIRCS), [*Gutowski et al.*, 1998]) climate modeling has demonstrated the usefulness of intercomparing model results. As an example, the evaluation of impacts of deforestation in the Amazonian River basin diverges considerably in magnitude and even sign of the impacts [*Lean and Rowntree*, 1997]. It is suggested therefore that more studies evaluating impacts of historical land use changes would supplement reported results for the United States.

Because of the high nonlinearity of the climate system, responses of regional climate to land use modification under extreme conditions such as drought and flood may differ from those under normal conditions. During a year with near-normal rainfall and temperature, crops and other vegetation grow and transpire at their typical rates, but hydrological anomalies often produce atypical evapotranspiration patterns. For example, in middle latitudes, during normal years most crops transpire more than forests, whereas during drought years some crops may transpire less than forests because of their shorter roots [*Campbell,* 1991]. Similarly, bare soil may evaporate more than crops during flood periods.

Addressing the above aspects, the present study simulates 1 month of each of three years representing normal, dry, and wet situations, thus providing a limited ensemble of events as an alternative to a multiyear continuous simulation. The present study has the following specific objectives: (1) to simulate regional climate impacts of land use changes caused by hu-

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man habitation over the central and western United States under normal climate conditions, (2) to contrast impacts under normal conditions with those under extreme conditions, and (3) to evaluate regional impacts of human activities on the severity of flood and drought. Some conceptual evaluations are provided in section 2, and land use and meteorological data sets are described in section 3. The simulation results are presented in sections 4 and 5. Section 4 provides analyses of land use effects on regional climate under normal climate conditions (1991), while section 5 contrasts the land use effects in flood (1993) and drought (1988) years.

2. Conceptual Analyses

Land surface characteristics may affect summer precipitation in the United States in several ways. First, surface processes affect the thermodynamic environment for deep convection through their control of fluxes of heat and moisture into the convective boundary layer (CBL). Thus they affect the moist static energy in the CBL, which is indicative of potential for deep convection. A consensus is evolving that greater surface wetness tends to increase the likelihood and amount of convective precipitation [e.g., *Betts et al.*, 1994; *Clark and Arritt,* 1995; *Segal et al.*, 1995]. This trend seems to occur even for an atmosphere that is initially moist, where it might be intuitively supposed that sensible heating of the boundary layer would be more important. The reason for this apparent contradiction is that increased surface wetness decreases the daytime Bowen ratio, while only mildly affecting the contribution by the surface moist enthalpy flux to the CBL specific static energy. The decreased Bowen ratio in turn produces a shallower CBL because the CBL growth rate to first order depends only on the sensible heat flux. The surface moist enthalpy flux therefore is concentrated within a shallower layer; additionally, the corresponding reduction of dry entrainment at the top of the CBL effectively increases specific moist static energy in the CBL, promoting development of moist convective systems and increasing precipitation amounts.

Second, surface processes may have local dynamic effects on the atmosphere. In the most direct sense, this could take the form of "inland breeze" type circulations between areas of sharply contrasting land use or surface wetness (termed "nonclassical mesoscale circulations" by *Segal and Arritt* [1992] and others). Available observations have not generally indicated occurrence of circulations of sea breeze intensity, although associated weak flow convergence occasionally can be sufficient to trigger convection. Surface processes also can influence other types of thermally forced circulations, such as daytime induced upslope flows or drylines. Such effects alter moisture transport or convergence and consequently modify rainfall distribution.

Third, surface properties may affect remotely regional-scale atmospheric dynamic features such as the low-level jet [*McCorcle,* 1988]. Regional climate studies have indicated that such modifications of the low-level jet may lead to alteration in rainfall fields [e.g., *Giorgi et al.*, 1996; *Paegle et al.*, 1996]. Also, land use modification may affect the meso-α scale convective "lid" that focuses development of deep convection [*Arritt et al.*, 1992; *Benjamin and Carlson*, 1986; *Lanicci et al.*, 1987].

The net effect of surface wetness on moist convective processes therefore is uncertain: A decreased Bowen ratio will tend to promote convective precipitation from the thermodynamic point of view, but in various situations it may reduce the intensity of thermally forced circulations that may be necessary to provide the trigger for release of convective instability. In summary, effects of surface processes on regional climate in the United States involve a complex interplay of both thermodynamics and dynamics locally and remotely.

Within the context of the present study, it is possible to evaluate the thermodynamic-related effects in a simplified manner. For this purpose the daytime surface moist static energy flux h is given by

$$h = H+ET = (1-\alpha)\, R_{S\downarrow} - R_{L\uparrow} - S \qquad (1)$$

where H and ET are the surface sensible and latent heat fluxes, α is surface albedo, $R_{S\downarrow}$ is downward shortwave solar radiation, $R_{L\uparrow}$ is upward net longwave radiation, and S is the heat flux into the ground.

The surface flux of moist static energy is conserved as long as the right-hand side of (1) is not affected by the change in land use, although changes in the partition between H and ET might occur. Increased albedo (α) would decrease h. On the other hand, change of bare soil into vegetation would reduce H and $R_{L\uparrow}$ and possibly decrease α. Overall in this scenario, h would increase while the Bowen ratio decreases, a situation which potentially supports deep convection. The results presented in this paper examine the impacts of changes in land use within the context of (1).

3. Selections of Land Use Data Sets and Model Schemes

3.1. Selection of Experimental Periods

The record-breaking 1988 midwest and Great Plains drought and 1993 Great Flood in the upper Mississippi basin are selected as the extreme dry and wet cases, respectively. The 1988 drought was most pronounced in May and June. Although considerable rain fell in July, the hydrological drought continued throughout the summer because of the extreme drying during previous months [*Trenberth and Guillemot*, 1996]. The summer of 1993 was the wettest in recent history over most parts of the upper Mississippi basin [*Kunkel et al.*, 1994]. A 1 month period covering the peak intensity of the extremes for both the drought and flood year, June 11 to July 11 [*Bell and Janowiak*, 1995], was selected for this study. Rainfall over most parts of the United States during summer 1991 was near normal, so the period of June 11 to July 11, 1991, is chosen to represent a normal year. The flow patterns in 1988 summer were dominated by a strong anticyclone over the western United States. The jet stream and associated storm tracks were shifted well north of their climatological position [*Mo et al.*, 1995]. On the other hand, the jet was displaced well to the south in 1993, so much moisture was supplied to the storm track.

3.2. Prescription of Land Use

Natural land use types were deduced from *Küchler* [1964] by remapping the vegetation classification, which has 116 categories, onto the Biosphere-Atmosphere Transfer Scheme (BATS) classification of 18 categories listed in Table 1. The current land use is adopted from the National Center for Atmospheric Research (NCAR) 0.5°x0.5° land use data set, which is used widely in model simulations [*Dickinson et al.*,

Table 1. Characteristic Values of Land Use Types [*Dickinson et al.*, 1992]

Variable	1	2	3	4	5	6	7	8	9	0	A	B	C	D	E	F	G	H
Maximum fractional vegetation cover	0.85	0.80	0.80	0.80	0.80	0.90	0.80	0.00	0.60	0.80	0.10	0.00	0.80	0.00	0.00	0.80	0.80	0.80
Roughness, m	0.06	0.02	1.00	1.00	0.80	2.00	0.10	0.05	0.04	0.06	0.10	0.01	0.03	.002	.002	0.10	0.10	0.80
Depth of rooting zone, m	1.0	1.0	1.5	1.5	2.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
Depth of upper soil layer, m	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fraction of water extraction by root	0.30	0.80	0.67	0.67	0.50	0.80	0.80	0.90	0.90	0.30	0.80	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vegetation albedo (λ<0.7 μm)	0.10	0.10	0.05	0.05	0.08	0.04	0.08	0.20	0.10	0.08	0.17	0.80	0.06	0.07	0.07	0.05	0.08	0.06
Vegetation albedo (λ>0.7 μm)	0.30	0.30	0.23	0.23	0.28	0.20	0.30	0.40	0.30	0.28	0.34	0.60	0.18	0.20	0.20	0.23	0.28	0.24
Minimum stomatal resistance, s m^{-1}	120	200	200	200	150	200	200	200	200	200	200	200	200	200	200	200	200	200
Maximum LAI	6	2	6	6	6	6	6	0	6	6	6	0	6	0	0	6	6	6
Stem area index	0.5	4.0	2.0	2.0	2.0	2.0	2.0	0.5	0.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Inverse square root leaf size	10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Light sensitivity factor	0.02	0.02	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06
Soil moisture availability	0.30	0.15	0.30	0.50	0.30	0.50	0.15	0.02	0.50	0.60	0.02	0.95	0.50	1.00	1.00	0.15	0.30	0.36

See caption of Figure 1 for the definitions of land use types.

1992]. The main difference between current and natural land use types is over the Great Lakes region and midwest where natural forest and native grass prairie have been replaced by cropland. Another region of significant changes is the southwestern United States where deciduous shrub and needleleaf forest were changed to evergreen shrubs and farmland (Figure 1). In both natural and current land use the semidesert and lake areas were unchanged. The semidesert over Nevada and New Mexico experienced little change in land use on large scales, although some local changes (unresolvable by our model) have occurred.

The most important land use parameters for this study include albedo (α), minimum stomatal resistance, and surface roughness z_0. Albedo differences between land use types are most pronounced in the near-infrared portion of the spectrum (see Table 1). Woodland, which has had the largest areal decrease, has about 20% smaller albedo than grass and crop lands. Crops have least minimum stomatal resistance (120 s m^{-1}) compared with all other vegetation types (200 s m^{-1}) (see Table 1). Woodland has larger roughness (z_0=0.8 m) than crops (z_0=0.06 m) and short grass (z_0=0.02 m). Woodland and cropland have larger maximum leaf area index (LAI =6) whereas short grassland has a value of only 2. The readers are referred to the BATS description for detailed explanations of the various variables [*Dickinson et al.,* 1992].

Compared with natural land use, the overall albedo decreased by about 2%, whereas surface soil moisture availability increased by 3% in current land use (Table 2). Equation (1) therefore suggests the likelihood of a slight increase in the surface moist static energy flux for present land use. Albedo has increased over the Great Lakes region, along the Arkansas-Mississippi border, and in parts of the west coast where crops have replaced woodland and deciduous shrub (Figure 2a). Albedo decreased over the western mountain region, where deciduous shrub was replaced by evergreen shrub, and over Mississippi and neighboring states, where natural woodland was replaced by needleleaf trees. Over the midwest, albedo remained unchanged since grass and crops are assumed to have the same albedo. The land use change over the western and central United States as defined in Figure 8 is also summarized quantitatively in Table 2.

Surface roughness, which is a function of vegetation height, decreased from a domain-averaged value of 0.281 m for natural conditions to 0.224 m for current land use (Table 2). This slight decrease in roughness is attributable to the expansion of cropland for which z_0=0.06 m as compared to 0.8 m for woodland and 0.1 m for tall grass (Figure 2b). The domain-averaged initial soil moisture availability *m* is 0.365 and 0.379 for the presettlement and current land use, respectively. The increase in *m* is contributed by cropland, which has an *m* value of 0.3 compared with 0.15 for grass prairie (Figure 2c). The *m* value of cropland is higher than other vegetation types. Both vegetation coverage (Figure 2d) and LAI (figure not shown) of the present day increase slightly because of the increase in cropland coverage which has a high value for both parameters (0.85 and 6 respectively).

3.3. Model and Parameterization Schemes

The regional climate model RegCM2, which was developed at NCAR based on the Penn State/NCAR MM4, is used for this study [*Giorgi et al.,* 1993a, b]. The RegCM2 incorpo-

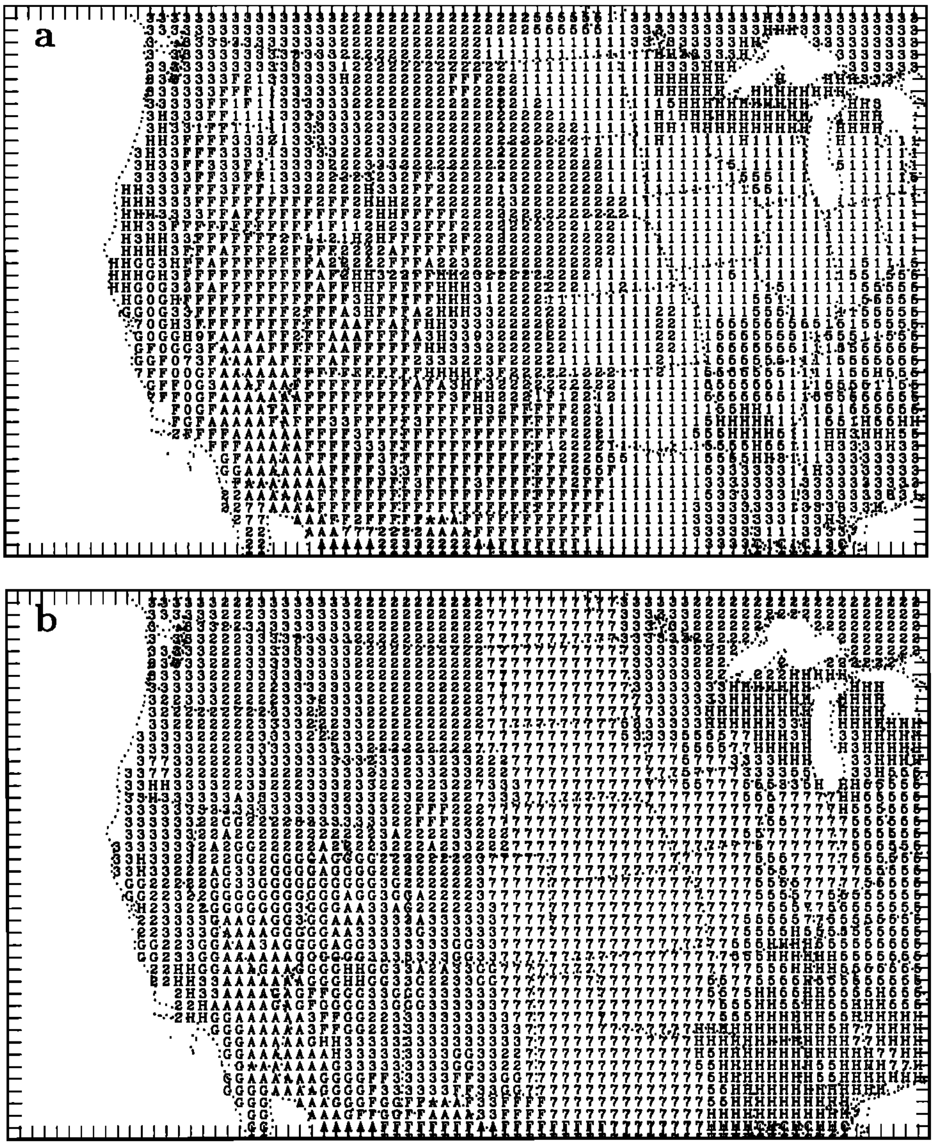

Figure 1. Land use type map: (a) present climatology and (b) potential natural land use adapted from *Küchler* [1964]. Numbers and letters denote the following: 1, crop/mixed farming; 2, short grass; 3, evergreen needleleaf tree; 4, deciduous needleleaf tree; 5, deciduous broadleaf tree; 6, evergreen broadleaf tree; 7, tall grass; 8, desert; 9, tundra; 0, irrigated crop; A, semi-desert; B, ice cap/glacier; C, bog or marsh; D, inland water; E, sea; F, evergreen shrub; G, deciduous shrub; H, mixed woodland.

rates the CCM2 radiation package [*Briegleb,* 1992] and the BATS version 1e [*Dickinson et al.*, 1992] surface package. The model domain covers 77x46 grid points with a horizontal resolution of Δx=50 km centered at (40.5°N, 106.5°W). The model is configured in this study with 14 layers in the vertical, at σ=0.995, 0.980, 0.950, 0.895, 0.815, 0.720, 0.615, 0.510, 0.405, 0.300, 0.210, 0.135, 0.070, and 0.020. The model top is located at 80 hPa. The simulation domain was chosen so that westerly inflow enters far from high mountains that can give rise to large interpolation errors.

Initial and boundary conditions (tendencies) were interpolated from the European Center for Medium-Range Weather Forecasts (ECMWF) T42 analyses. Boundary conditions were updated every 6 hours by linear interpolation in time from 12-hourly analyses. Within the buffer zone near the boundaries, the model-predicted variables were nudged to ECMWF analyses. It should be noted that prescription of lateral boundary conditions based on present observations in the natural simulation inevitably produces some biases in predicted fields.

Two of the most important parameterization schemes relevant to this study are those for surface processes and cumulus convection. The state-of-art BATS version 1e is chosen for the surface processes, while the modified Kuo scheme is chosen for cumulus convection in this study [*Anthes*, 1977; *Kuo*, 1974]. This relatively simple cumulus parameterization scheme was chosen for the following reasons: (1) Our previous study [*Pan et al.*, 1996] showed that the Kuo scheme is more sensitive to surface wetness than the Grell scheme [*Grell*, 1993]. Use of the Kuo scheme therefore amplifies potential change in rainfall because of land use changes, so that

Table 2. Domain- and Subdomain-Averaged Land Use Parameters

Land Use Type	α	m	f_v	LAI	z_0
		Whole Domain			
Natural	0.262	0.365	0.625	4.313	0.281
Current	0.257	0.379	0.635	4.343	0.224
		Western United States			
Natural	0.267	0.283	0.675	4.409	0.384
Current	0.251	0.258	0.676	5.108	0.278
		Central United States			
Natural	0.285	0.205	0.793	5.802	0.239
Current	0.289	0.258	0.817	4.774	0.113

The parameters are as follows: surface albedo (α), soil moisture availability (m), vegetation cover (f_v), leaf area index (LAI), and surface roughness (z_0 in meters). The western and central United States are defined in Figure 8a.

our results can be interpreted as providing an upper limit for the sensitivity to land use. (2) A previous similar study [*Copeland et al.*, 1996] was performed using the Kuo scheme, so that its adoption here facilitates comparison with previous results.

4. Results of Simulations for Normal Year 1991

4.1. Model Validation

Model skill in reproducing the real atmosphere was evaluated in the present study. All validating observations are from the ECMWF T42 analyses except for rainfall, which is from the National Climate Data Center (NCDC) Cooperative Hourly Precipitation. Initial soil moisture content is given by climatological values. All figures in this subsection are from the 1991 simulation, and model validations are from the simulation with current land use unless stated otherwise.

The temporal variation of surface pressure is a gross measure of synoptic activity within the model domain. The observed surface pressure exhibits passages of several synoptic waves (Figure 3). The simulated domain average surface pressure follows the observed trend quite well, although the simulated pressure is somewhat lower than observed for much of the period. The model tends to give a low bias for pressure but is within 1 hPa most of the time, with a maximum error less than 1.5 hPa (Figure 3). The monthly mean surface pressure at 0000 UTC shows a small positive bias over the western mountain region and a somewhat larger negative bias in the east central United States (Figure 4). These biases appear to be related to the terrain elevation, and thus are likely attributable to difference in terrain height between our grid and the coarse ECMWF analyses. The errors are relatively large along the west coast, which perhaps can be attributed to the effects of complex terrain as well as the relative lack of upstream observations (*i.e.*, over the Pacific Ocean) to provide appropriate boundary conditions. The overall error magnitudes are small, within 1 hPa over most of the domain except for those negative centers where error reaches 2-3 hPa. In general, the bias in domain average is not important as long as the horizontal pressure gradient of meteorological systems remains unaffected.

We choose a midtroposphere level (σ=0.51, roughly 500 hPa) to evaluate model skill since this is one of the most im-

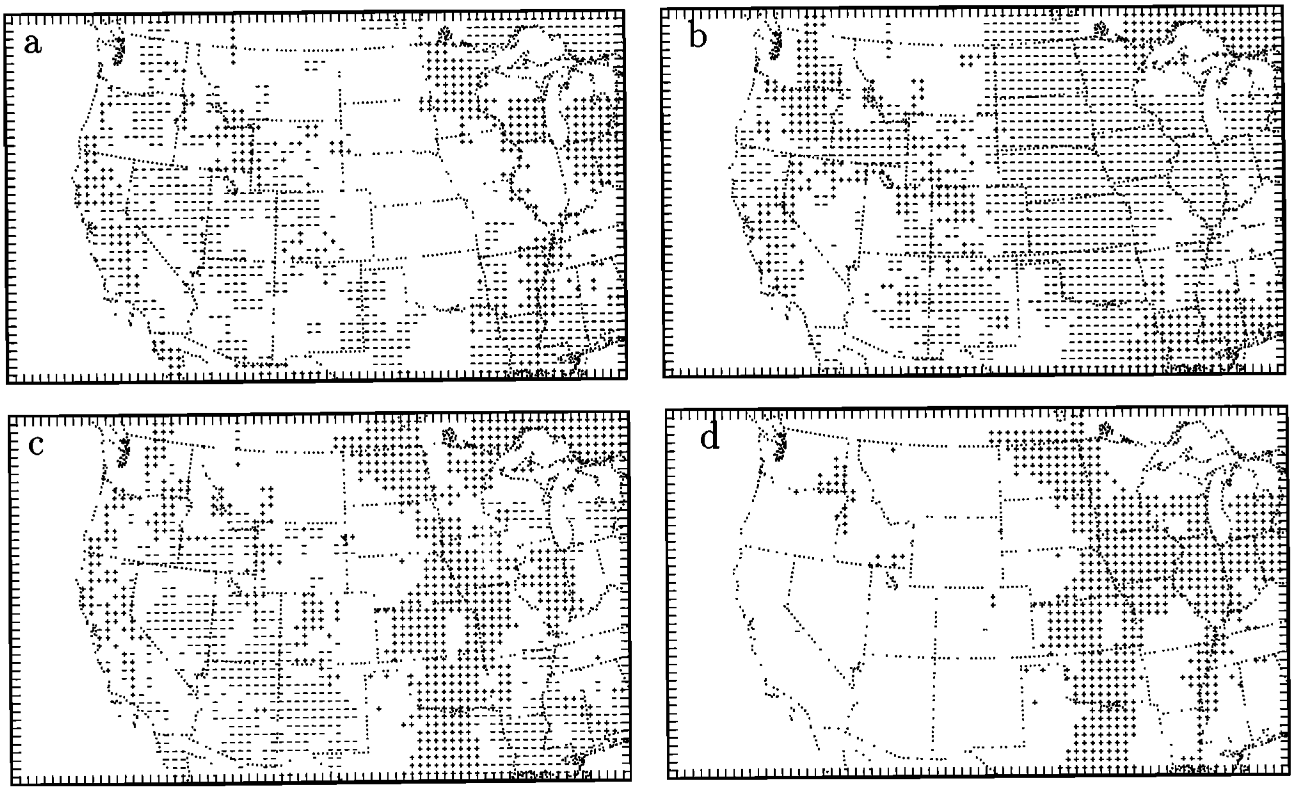

Figure 2. Trend of change in various land use parameters from natural to current land use (the plus denotes increase; minus denotes decrease): (a) albedo, (b) surface roughness (meters), (c) moisture availability, and (d) fractional vegetation coverage.

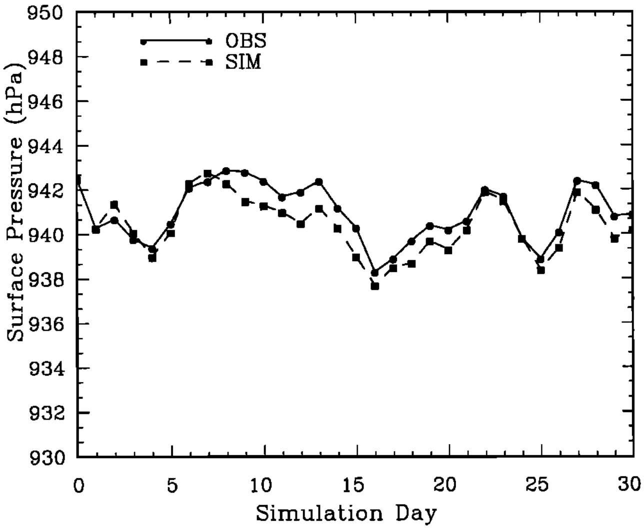

Figure 3. Time series of simulated domain-averaged surface pressure compared with observation (1991).

portant levels that steer the movement of atmospheric systems. Observed wind speed averaged over the whole domain at 0000 UTC varied markedly in time, with high values of 15 m s^{-1} and low values of 10 m s^{-1} (Figure 5a). The simulated wind speed closely followed the observations throughout the period. It is noteworthy that the simulated peak winds had a 1-2 day time lag during the later stage of the simulation, a manifestation of limited area boundary forcing.

The observed temperature at σ=0.51 exhibited a gradual warming trend throughout the period (Figure 5b). Simulated temperature followed this trend reasonably well, although it tended to be biased slightly cold most of the time. The largest error was about 1.5 K, and average error was less than 0.5 K.

The large temporal and spatial variability of rainfall, as well as the multiplicity of nonlinear processes involved in its prediction, makes it one of the most difficult variables to simulate. For these reasons, precipitation is the variable simulated with least skill in almost all modeling studies. Observed rainfall during the 30-day period in 1991 exhibited lo-

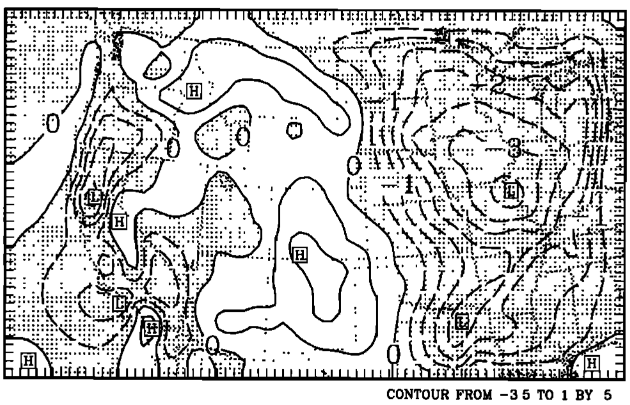

Figure 4. Spatial distribution of the difference (hPa) in 30-day averaged surface pressure between the simulation and observation in 1991. Contour interval is 0.5 hPa. Areas of negative values are shaded.

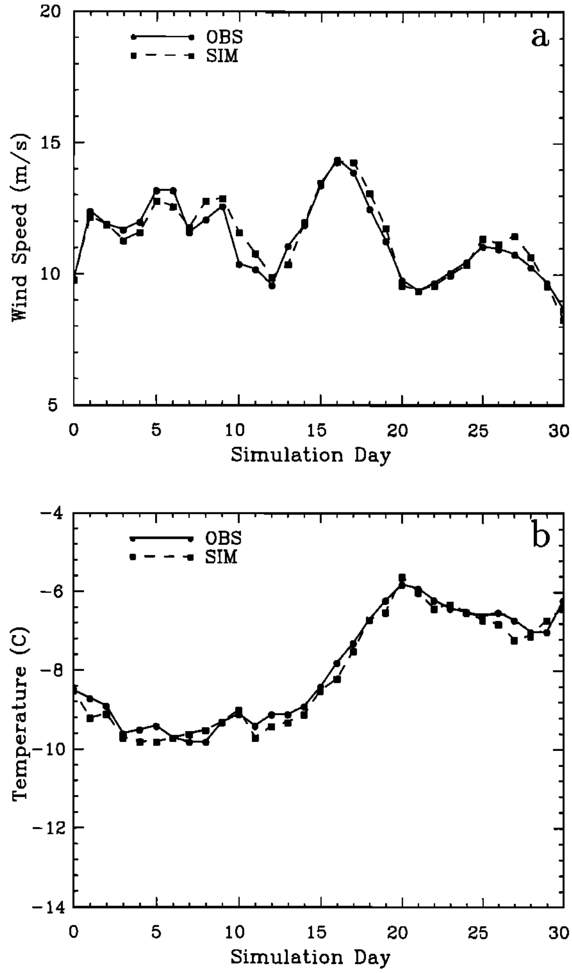

Figure 5. Time series of simulated domain-averaged variables at σ =0.51 (~500 hPa) compared with observation (1991): (a) wind speed and (b) temperature.

cal maxima along the United States-Canada border and in the Louisiana-Mississippi-Alabama (LA-MS-AL) region at the southeast corner of the domain (Figure 6a). The simulation reproduced heavy rainfall along the United States-Canada border and part of Iowa (Figure 6b). The model failed to produce heavy rainfall in LA-MS-AL, which was due partly to its proximity to the model boundaries and partly to the small scale of convective rainfall events often associated with local sea breezes that are not resolved by the model. The model predicted excessive rainfall in Oklahoma and New Mexico probably because of model artifacts known as grid point storms [*Giorgi et al.*, 1993b]. It is possible also that excessive moisture was advected from LA-MS-AL, where the model should have produced heavy rainfall.

The domain-averaged cumulative rainfall followed the observed trend even though the model misplaced the exact locations of rainfall centers (Figure 7). The simulated domain total rainfall was lower than observed near the beginning of the simulation, due partly to model spin-up effects. Simulated rainfall exceeded observed amounts in the later part of the simulated period, approximately balancing the deficit of the first half month. Combination of results from Figures 6 and 7 provides an initial measure of the model performance.

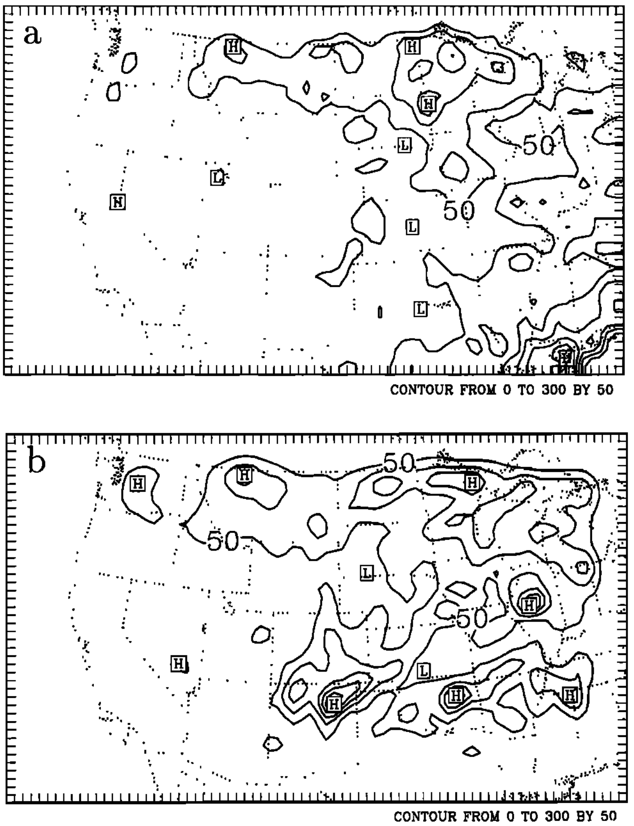

Figure 6. Spatial distribution of (a) observed and (b) simulated 30-day accumulated rainfall (mm) (1991). Contour interval is 50 mm.

In summary, the simulated domain-averaged surface pressure and 500 hPa wind and temperature resembled observations well, and simulated domain-averaged rainfall was realistic, although the model did not reproduce details of the rainfall distribution. These results indicate that the model is reasonably skillful in reproducing real meteorological processes.

4.2. Distribution of Surface Fluxes and Precipitation

Differences in *ET* between current and natural land use are positive over most of the central United States where crops replaced either grass prairie or woodland, both of which consume less water than crops (Figure 8a). (We express cumulative fluxes as equivalent precipitation in order to facilitate a hydrological perspective; 1 mm of water is equivalent to an accumulated energy input of 2.5 MJ m^{-2}.) Negative *ET* differences were found in the southwest United States where evergreen shrub has replaced deciduous shrub. Differences in sensible heat flux were similar to *ET* differences but with opposite sign (Figure 8b). The solar radiation difference field (Figure 8c) correlates well with albedo changes (see Figure 2a) in the western United States, where normally low cloud coverage prevails, so decreased albedo caused larger radiation absorption. Over the east central United States the correlation between albedo and incoming radiation is less clear because of the influence of clouds. The increase in solar radiation in the Great Lakes region where the surface albedo is relatively high may be explained by the reduced cloudiness as implied by corresponding decreased rainfall (Figure 8d).

The difference fields in rainfall between current and natural land use exhibit several positive and negative centers of large magnitude, although the domain total rainfall differs only slightly between the two experiments. The difference pattern is associated with the rainfall pattern itself rather than the land use change pattern (Figure 8d). The dipole structure can be explained by the horizontal displacement of rainfall areas. This negative spatial correlation was found by other modeling studies [e.g., *Paegle et al.*, 1996] and observational studies [e.g., *Rasmussen*, 1967].

4.3. Subdomain-Averaged Surface Fluxes

As discussed in section 2 within the context of land use changes and corresponding effects on rainfall, changes in summer precipitation are related to modification of both thermodynamic and dynamic processes. Based on the flux and rainfall distribution in Figure 8, we subdivided the simulation domain into western (drier) and eastern (wetter) subdomains called western United States and central United States, respectively (see Figure 8a for illustration of the subdomains). The 10-grid point perimeter of the domain was excluded to avoid possible boundary effects while computing energy budgets. Table 3 summarizes subdomain averages of various surface energy components and rainfall for the 30-day accumulation. Over the central United States, an average of 61.8 mm *ET* was simulated for the current land use compared with 52.5 mm for the natural land use, a 9.3 mm or 18% increase. On the other hand, sensible heat flux decreased by 5.9 mm in response to the land use change, giving a 2.4 mm total gain in enthalpy for current land use. Rainfall increased 2.6 mm (4%) with current land use; thus, the conceptual evaluation of section 2 suggests that for the simulated period in 1991 thermodynamic processes dominated, as a whole, over dynamic processes in producing land use effects on rainfall. It is noteworthy that of the 9.3 mm increase in *ET*, 2.6 mm may effectively translate into rainfall, implying a 28% recycling rate assuming simulated moisture flux divergence was the same for the two types of land use. Over the western United States both *ET* and rainfall changes were negative, though small compared to the central United States.

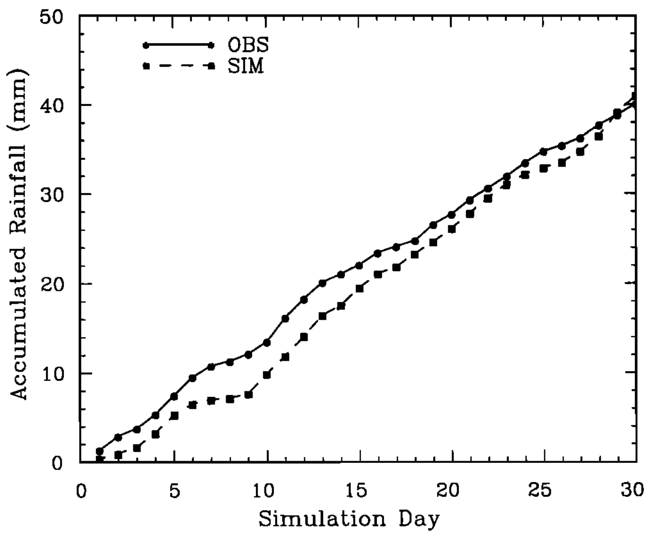

Figure 7. Time series of accumulated domain-averaged rainfall, simulated amount compared with observations (1991).

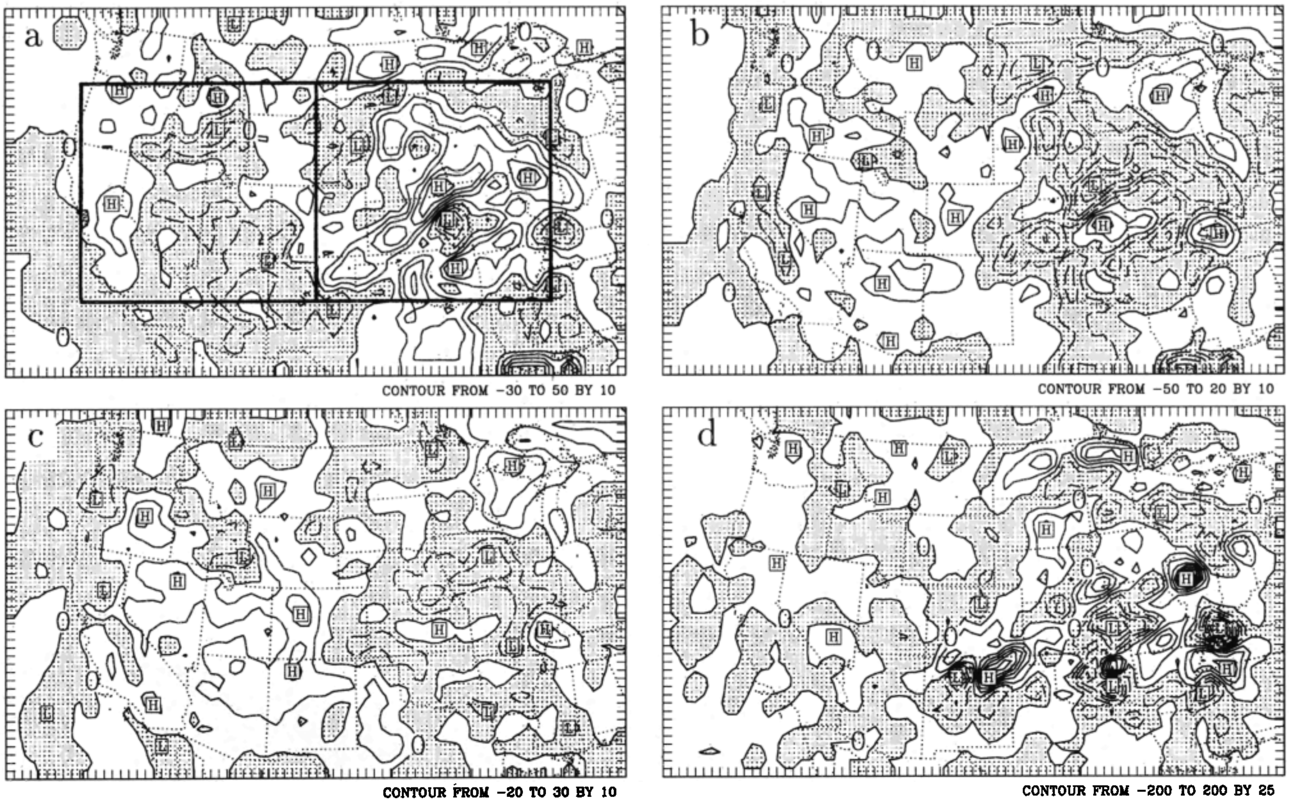

Figure 8. Difference fields (mm) in 30-day accumulated surface fluxes between current and natural land use (1991): (a) latent, (b) sensible, (c) incoming solar radiation, and (d) rainfall. Contour intervals are 10 mm (1 mm ~ 2.5 MJ m^{-2}) except for Figure 8d where it is 25 mm. Areas of negative values are shaded. The inner thick solid lines in Figure 8a represent the boundaries of the western and central United States defined in this study.

Latent heat flux averaged over 1800-2100 UTC (the usual time of daily maximum surface heat fluxes) was rather consistently about 20 W m^{-2} larger for current land use in the central United States but showed little difference in the western United States (Figures 9a and 9b). Correspondingly, sensible heat flux showed a similar trend but smaller and with opposite sign to latent heat flux between the two simulations (not shown). Differences between the two land use types were larger for *ET* than *H*. This is expected because cropland expansion is the primary land use change, and the most prominent impact of crops on the energy budget is their lower stomatal resistance. This means that the *ET* increase over crop-

Table 3. Thirty-Day Subdomain Accumulated Evapotranspiration (*ET*), Surface Moist Enthalpy Flux (*h*), Incoming Radiation (R_S), and Rainfall (*P*) for the Simulations With Natural Land Use and the Changes in These Quantities With Current Land Use

Land Use Type	1988		1991		1993		Total	
	W	C	W	C	W	C	W	C
				ET				
Natural	43.5	52.9	37.5	52.5	35.5	69.1	38.8	58.2
Current minus natural	-1.0	6.1	-1.6	9.3	-0.8	4.5	-1.1	6.6
				h				
Natural	127.4	129.5	127.5	128.8	132.9	136.7	129.3	131.7
Current minus natural	1.7	0.1	2.0	2.4	2.9	0.0	2.2	0.8
				R_S				
Natural	297.5	256.8	288.7	260.7	313.9	257.3	300.0	258.3
Current minus natural	3.0	-3.2	6.0	-3.0	5.5	-1.7	4.8	-2.6
				P				
Natural	37.4	88.5	29.2	73.1	21.7	112.1	29.4	91.2
Current minus natural	2.6	-3.4	-0.1	2.6	0.3	-8.2	0.9	-3.0

The values are for western United States (W) and central United States (C); see Figure 8a for subdomain illustration. All units are in millimeters (1 mm ~ 2.5 MJ m^{-2}).

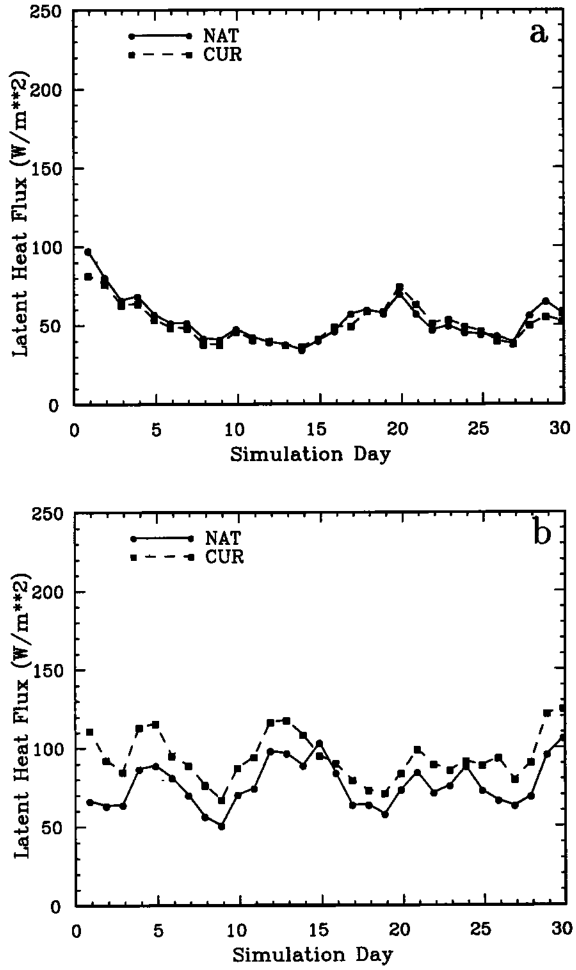

Figure 9. Time series of surface latent heat flux averaged over subdomains between 1800 and 2100 UTC (1991): (a) western United States and (b) central United States.

land was larger than the decrease in sensible heat flux, reflecting changes in the terms on the right-hand side of (1). The surface under present land use absorbed slightly more solar energy since it has smaller albedo (Table 2).

4.4. Screen Height Variables

Variables at screen height (2 m above ground level (AGL)) are interpolated between the surface (at z_0) and lowest model level (σ=0.995, about 40 m AGL) using the logarithmic profile corresponding to neutral stratification [*Dickinson et al.*, 1992]. For most vegetation types, z_0 is much less than 2 m, except for evergreen broadleaf trees which do not exist in the current simulation domain.

The 30-day average wind speed increased over the central United States, where cropland of small surface roughness (z_0 =0.06 m) replaced tall grass prairie of z_0 =0.1 m, and over the southwest United States, where crops and shrub replaced woodland (Figure 10a). Temperature patterns show a general cooling over the central United States and slight warming in the west (Figure 10b). The cooling is likely associated with the increased *ET* under current land use, and the warming is related to the increased radiation and sensible heat flux from the ground and to albedo decrease. Mixing ratio increased in the central United States and decreased in the western United States (Figure 10c) in direct relation to the *ET* distribution. Temperature differences also are consistent with differences in latent heat flux distribution in Figures 8a and 8b. Wind speed at 2100 UTC averaged over the subdomain was stronger with larger amplitude of the fluctuations in the central than western United States, indicating more intense synoptic systems. Wind speed for current land use is about 0.3-0.5 m s^{-1} larger than for presettlement because of the replacement of forest with crops (Figure 11). The current land use showed about 0.5 K lower air temperature due to more evapotranspiration over the central United States (Figure 12).

Summer temperature (June, July, and August (JJA)) for the last 100 years, which is shorter than the period during which the land use changes considered in the present study took

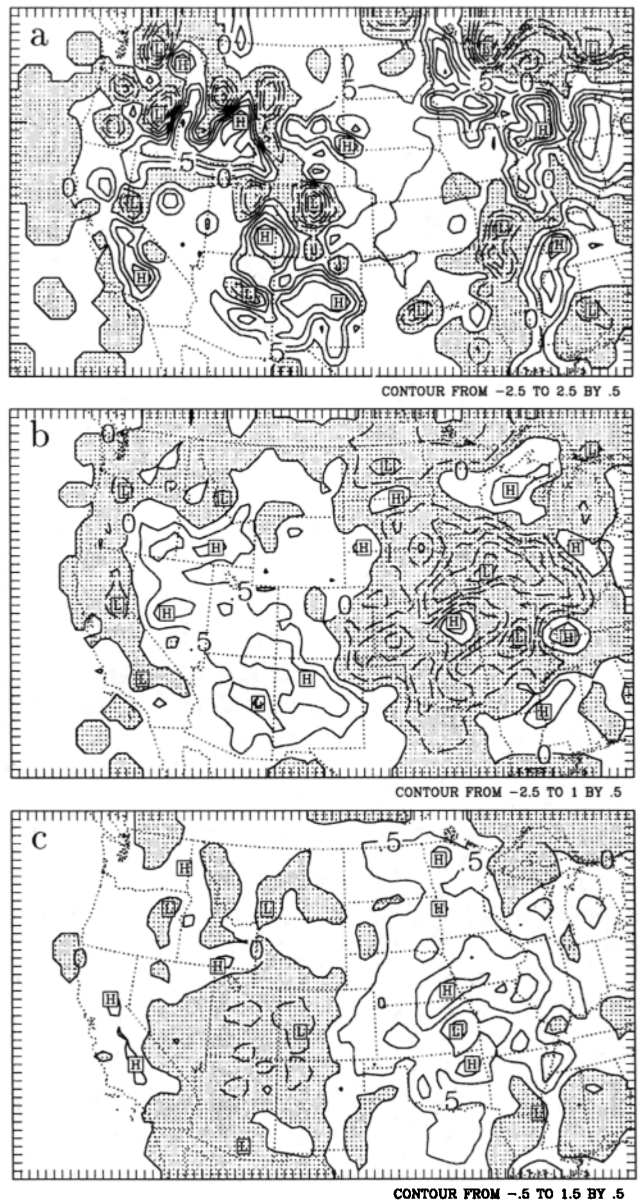

Figure 10. Difference fields in 30-day averaged variables at screen height (2 m) between current and natural land use (1991) at 2100 UTC: (a) wind speed (m s^{-1}), contour interval is 0.5 m s^{-1}; (b) temperature (K), contour interval is 0.5 K; (c) mixing ratio (g kg^{-1}). Contour interval is 0.5 g kg^{-1}. Areas of negative values are shaded.

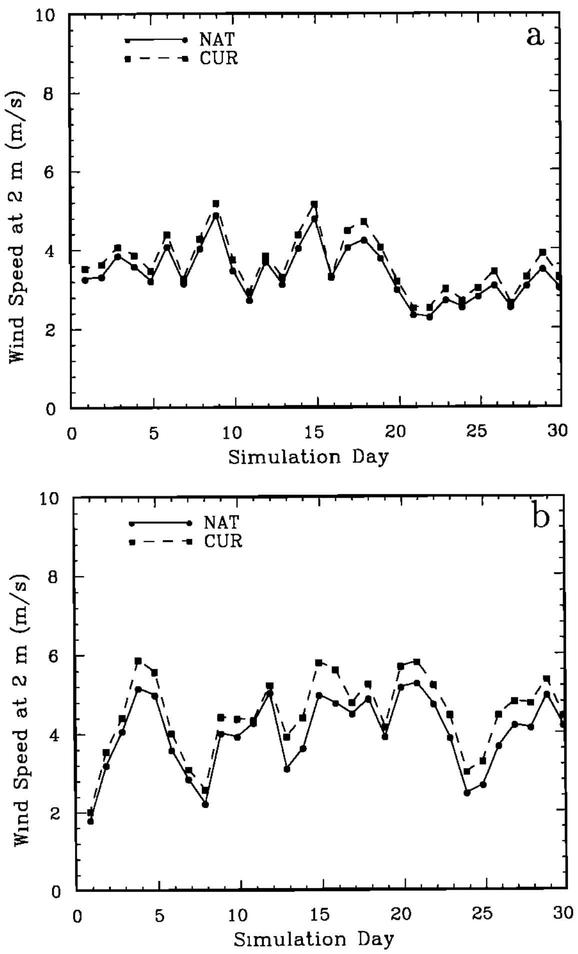

Figure 11. Time series of averaged wind speed at screen height (2 m) in 1991 at 2100 UTC: (a) over western United States and (b) over central United States.

place, has been observed to be decreasing over the lower Mississippi basin and the Gulf Coast and increasing over the western mountain region [*Karl et al.*, 1994]. The general pattern of observed trends, with cooling in the east central United States and warming in the western United States, resembles the results presented in Figure 12 and might suggest consistency between observations and model results. There are no extensive wind and mixing ratio records to verify our simulation of these variables. However, our subdomain-averaged increase in wind speed and mixing ratio for present land use is consistent with results of *Copeland et al.* [1996].

5. Flood and Drought Contrast

5.1. Flood of 1993

Subdomain-averaged *ET* differences between the two simulations (current and natural) were of similar trend as those for 1991, whereas the rainfall trend was reversed (see Table 3) for both western and central United States. Rainfall decreased by 8.2 mm (7%) while *ET* increased 4.5 (7%) over the central United States. Based on discussions in section 2 this pattern would indicate the dominance of large-scale dynamic effects on rainfall over thermodynamic effects. It is worth noting that simulations by *Giorgi et al.* [1996] and *Paegle et al.* [1996] indicated that wetting of the surface in the central United States yielded a decrease in rainfall over much of this region. The pattern shown in Table 3 is consistent with their findings.

The overall rainfall change pattern does not match that for *ET* in Figure 13. Average rainfall over the central United States actually decreased while *ET* increased. However, maxima and minima for *ET* and rainfall changes tend to coincide. This suggests that the decrease (increase) in rainfall was associated with reduced (increased) *ET* only on the local scale, but not on the domain scale.

To explore why similar surface flux differences cause opposite rainfall responses between normal and flood years, the screen-height temperature (Figure 14a) at the negative center (grid point (61, 21) in Figure 13b) is examined. It reveals that temperature for current land use is lower than that for natural land use, especially during the earlier days of the simulation. This lower temperature and reduced evapotranspiration and convection could be in part the cause of reduced rainfall amount.

The v component wind, which furnishes moisture to warm season rainfall systems near the central United States, at this same grid at σ=0.895 is noticeably weaker with current land use, implying weakened nocturnal low-level jet (Figure 14b). A weaker wind lowers *ET* and moisture convergence [*Lean and Rowntree*, 1997], and likely would reduce rainfall. It is

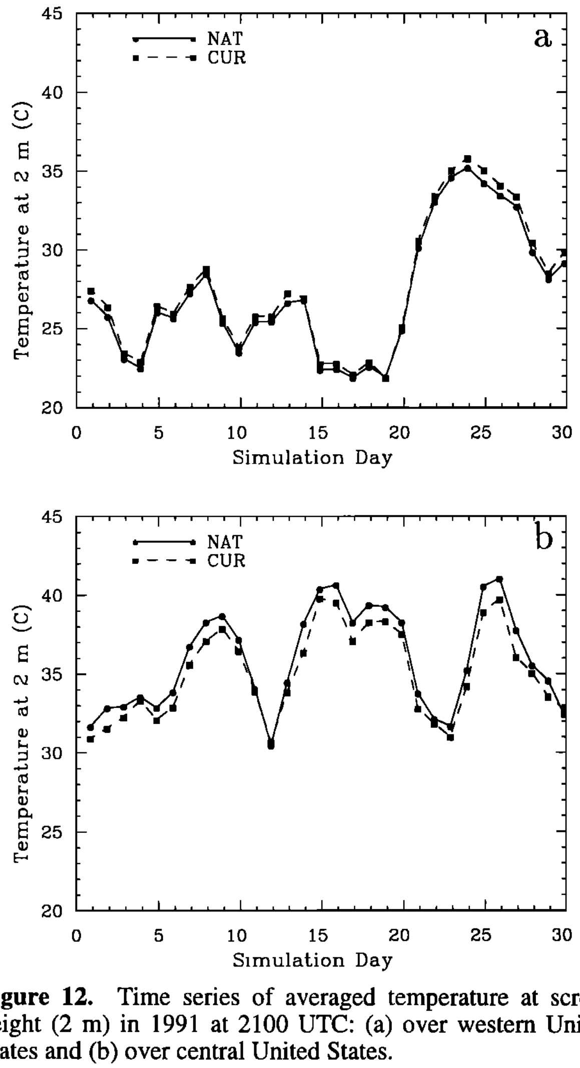

Figure 12. Time series of averaged temperature at screen height (2 m) in 1991 at 2100 UTC: (a) over western United States and (b) over central United States.

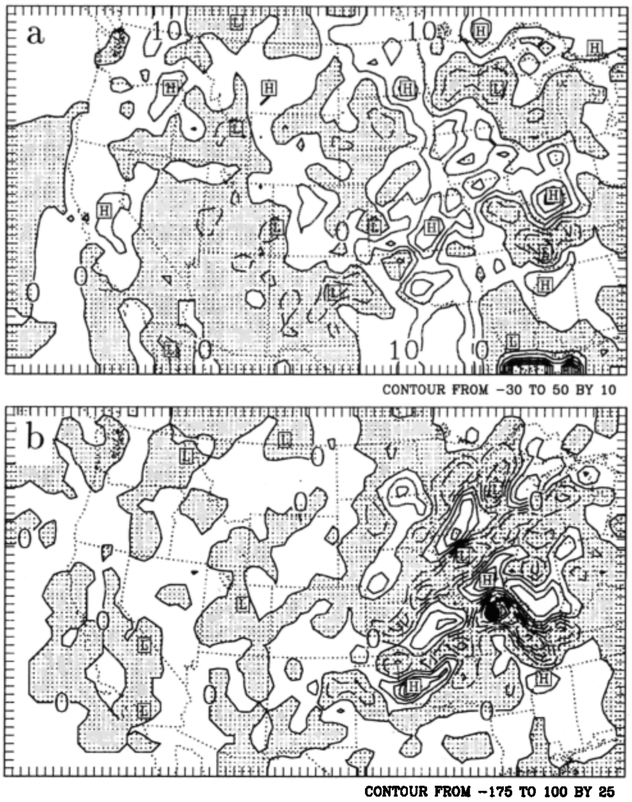

Figure 13. Difference fields (mm) in 30-day accumulated (a) latent heat flux and (b) rainfall between current and natural land use (1993). Contour intervals are 10 mm (1 mm ~ 2.5 MJ m^{-2}) for Figure 13a and 25 mm for Figure 13b. Areas of negative values are shaded.

worth noting that the intensification of the low-level jet over the central United States was one of important factors for intense rainfall events during the 1993 flood [*Arritt et al.*, 1997].

5.2. Drought of 1988

Subdomain average surface flux changes between the two land use scenarios are similar to those for the normal year. However, the rainfall difference pattern is the same as in 1993 (see Table 3). Spatial correlations between *ET* and rainfall difference fields are not as clear as in 1991 and 1993 (Figure 15). Atmospheric dynamics and thermodynamics in 1988 on average did not support the development of precipitation. It is therefore less likely that the small increase in *ET* would be conducive to deep convection compared with the other two years. The difference field in rainfall between current and natural land use has localized large values even though subdomain averages are very similar between the two experiments. These localized "storms" are artifacts that tend to occur when the atmosphere is dry since there are fewer synoptic systems to organize the localized individual convection [*Giorgi et al.*, 1993b; *Pan et al.*, 1996].

6. Hypothetical Uniform Cropland

Estimation of natural land use inevitably introduces uncertainty, which may mask the small impact of different land use. To project the maximum possible effects of this trend, we consider a hypothetical situation where land use is uniform cropland except over the water and desert. Such experiments are commonly used to study land use impact [e.g., *Dickinson and Henderson-Sellers,* 1988; *Lean and Rowntree,* 1997]. Crops are assumed to cover 85% of the surface with 15% bare soil within each grid box during summer (Table 1).

ET increases over the whole western United States because of the hypothetical replacement of grassland and woodland by crops. However, over much of the north central United States where cropland is dominant already, a decrease in *ET* is simulated (Figure 16a). This could be due to increased atmospheric water vapor which decreases the moisture gradient between the surface and the atmosphere. Sensible heat flux decreases almost everywhere except over the desert, where it is assumed that no crops are present, and the Great Lakes region (Figure 16b). Uniform cropland produces more moist static energy despite lower absorbed solar energy (Figure 16c). This is because crops transpire more due to their lower stomatal resistance; this increased *ET* cools the surface and thus reduces outgoing longwave radiation.

Absorbed solar radiation at the surface decreases over the entire western United States because crops have larger albedo (Figure 16c). The increase in radiation over the Great Lakes and Oklahoma is likely attributable to decreased cloudiness, as implied by decreased rainfall (Figure 16d). The rainfall dif-

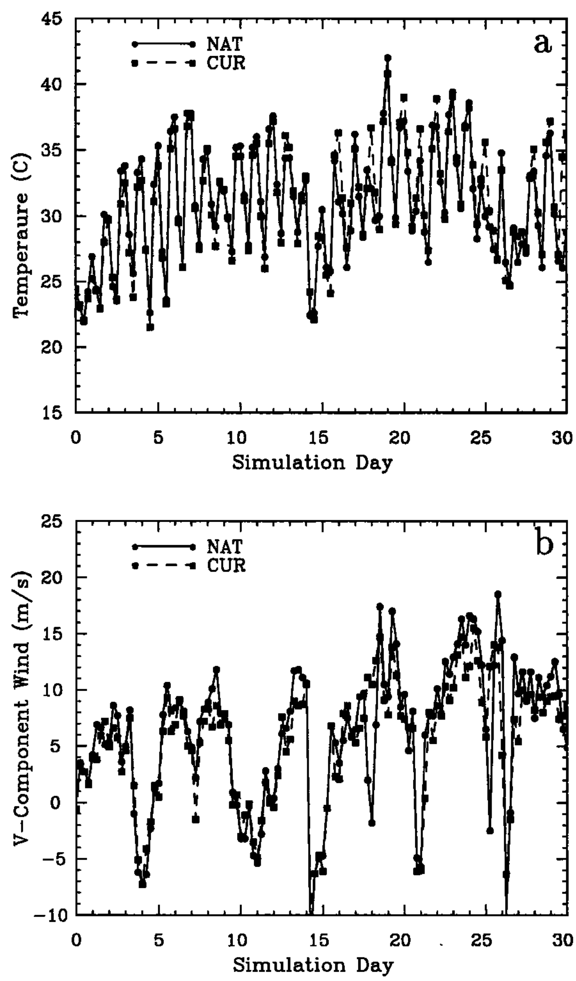

Figure 14. Six-hourly (a) temperature and (b) v component wind at σ =0.895 at grid point (61,21) for 1993 indicated by the solid circle in Figure 13b.

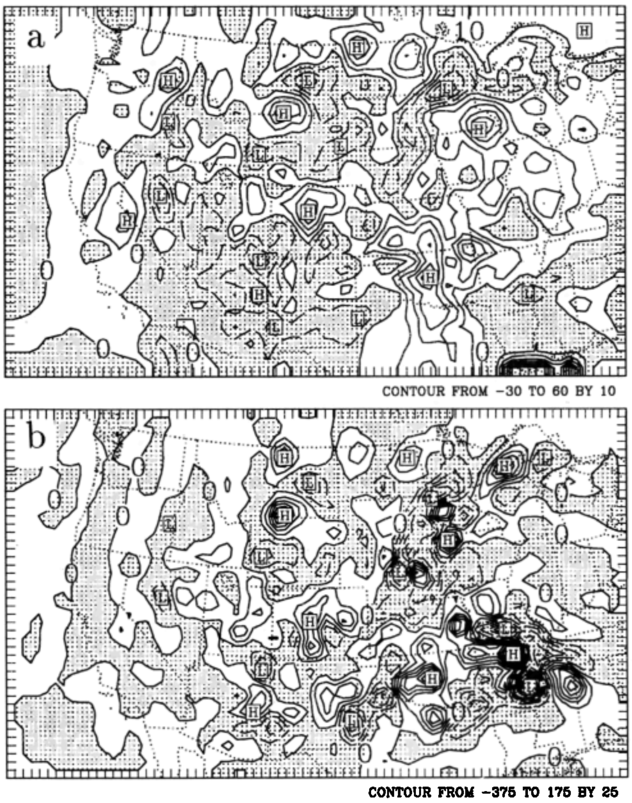

Figure 15. Difference fields (mm) in 30-day accumulated (a) latent heat flux and (b) rainfall between current and natural land use (1988). Contour intervals are 10 mm (1 mm ~ 2.5 MJ m^{-2}) for Figure 15a and 25 mm for Figure 15b. Areas of negative values are shaded.

ference is mainly limited to heavy rainfall areas but with larger extent of positive areas. Winds increase noticeably over the western mountain area, Mississippi valley, and Great Lakes forests because of smaller surface roughness of crops compared with forests. Table 4 compares the subdomain averages of fluxes and rainfall between the current and uniform crop simulations.

7. Summary and Discussion

Impacts of human settlement on regional summer climate over the central and western United States were examined by considering three vegetation scenarios (presettlement natural, current, and hypothetical cropland) under normal, flood, and drought "climates". It was found that responses to land use changes of surface latent and sensible heat fluxes, and thus surface air temperature, moisture, and winds, were nearly independent of climate regime, whereas rainfall showed strong case-to-case variations because of the multiplicity of dynamic and thermodynamic processes involved in precipitation.

Replacement of native grass prairie by cropland in the Great Lakes region and midwest and deciduous shrub and needleleaf forest by evergreen forests suggests that current land use has warmed and dried most parts of the western United States and cooled the central United States. Under normal year conditions, average evapotranspiration (*ET*) and rainfall under current land use increased by 9.3 mm (18%) and 2.6 (8%), respectively, over the central United States whereas they decreased slightly in the western United States. Under extreme year conditions, current land use exhibited an in-

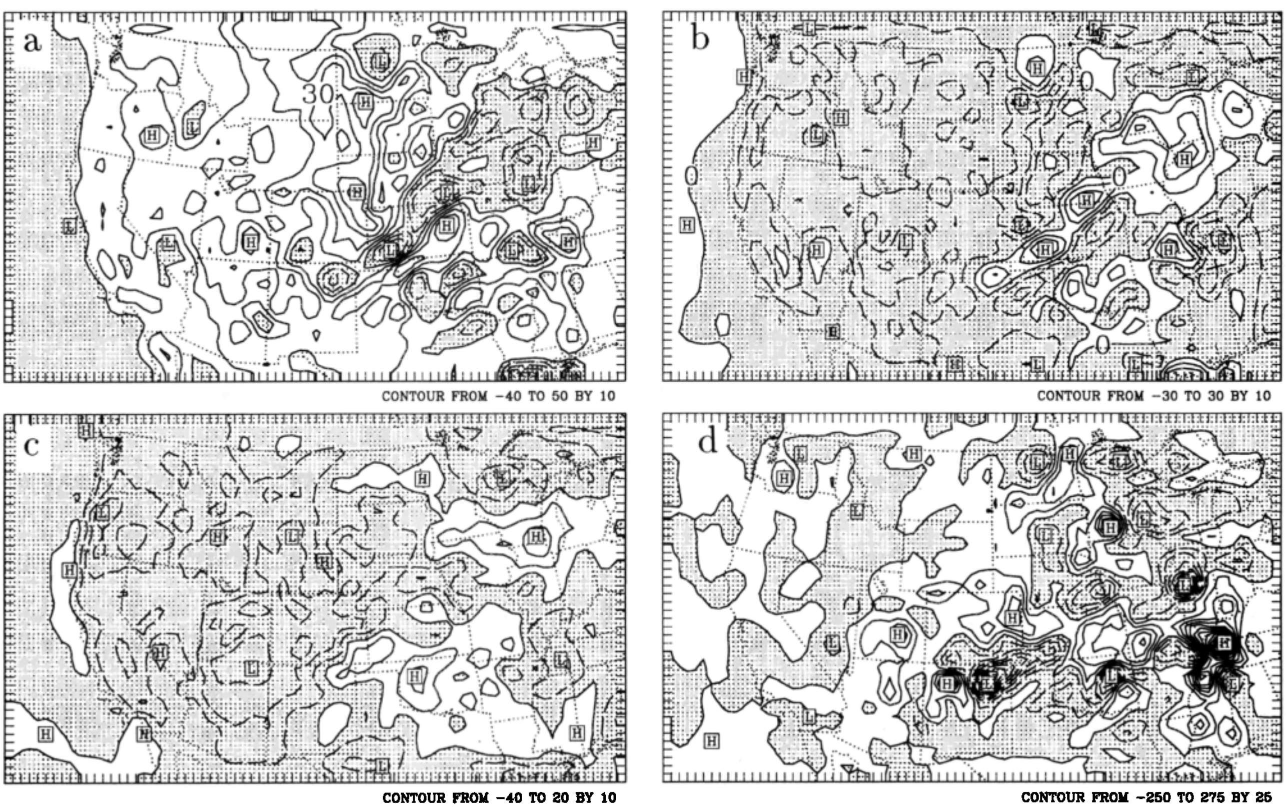

Figure 16. Difference fields (mm) in 30-day accumulated fields between the hypothetical uniform crop and current land use (1991): (a) latent heat flux, (b) sensible heat flux, (c) incoming radiation, and (d) rainfall. Contour intervals are 10 mm (1 mm ~ 2.5 MJ m^{-2}) except for Figure 16d, where it is 25 mm. Areas of negative values are shaded.

Table 4. Thirty-Day Subdomain Accumulated Evapotranspiration (*ET*), Surface Moist Enthalpy Flux (*h*), Incoming Radiation (R_S), and Rainfall (*P*) for the Simulations With Current Land Use and the Changes in These Quantities With Uniform Crops

Land Use Type	1988		1991		1993		Total	
	W	C	W	C	W	C	W	C
				ET				
Current	42.5	59.0	35.9	61.8	34.7	73.6	37.7	64.8
Crop minus current	12.4	8.6	12.5	7.4	12.3	7.5	12.4	7.8
				h				
Current	129.1	129.6	129.5	131.2	135.8	136.7	131.5	132.5
Crop minus current	0.6	5.8	-0.6	4.6	-0.6	3.2	-0.2	4.5
				R_S				
Current	300.5	253.6	294.7	257.7	319.4	255.6	304.9	255.6
Crop minus current	−14.8	-0.6	-18.1	-0.3	-18.6	-4.7	-17.2	-1.9
				P				
Current	40.0	85.1	29.1	75.7	22.0	103.9	30.3	88.2
Crop minus current	1.3	-2.6	3.9	-6.5	3.7	-4.0	3.0	-4.4

The values are for western United States (W) and central United States (C); see Figure 8a for subdomain illustration. All units are in millimeters (1 mm ~ 2.5 MJ m^{-2}).

crease in rainfall over the western United States and decreased rainfall over the central United States. The rainfall increase in the western United States was attributed to the increased surface moist static energy, although *ET* was slightly reversed. The decreased rainfall with increasing *ET* in the central United States was associated with weakened low-level jet due to reduced daytime sensible flux over the southern Great Plains. This suggests that rainfall variations were dominated by dynamic processes. For the central United States, temperature showed a slight cooling with current land use, which resulted from stronger cooling over the midwest and Great Lakes region, where crops replaced grass prairie and natural woodland. This result suggests that hypothetical CO_2-induced global warming over the United States may be offset to some extent by the land use changes. For the western subdomain, slight warming associated with increased sensible heat flux was simulated.

The 1991 normal year simulation produced a 4% increase in domain total rainfall in response to changes from the presettlement to current land use. This value is in close agreement with results of the *Copeland et al.* [1996] study where a 5% increase was obtained for the same land use change scenario. Observed rainfall over the United States has increased by about 1% over the last 100 years [*Plantico et al.*, 1990], recognizing that land use changes occurred well beyond 100 years back. However, our simulations for flood and drought years showed a decrease in rainfall. This difference in rainfall responses to land use changes between the normal year and extreme years deserves more investigation. Our hypothetical uniform crop simulation indicated a decrease in rainfall with increased *ET* over the central United States. This result is consistent with the results from *Bonan's* [1997] maximum agriculture simulations, even though our regional simulation covers only 1 month with a 50 km resolution compared with his 5-year global simulation with 200 km resolution.

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